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Table of Contents

Section		Page
	SUMMARY	1
I.	INTRODUCTION	2
II.	PROCESSING DEVELOPMENT OF MCM STRUCTURE	2
	A. Summary of MCM Development Plan	3
	B. Optimization of YBCO on Vendor-Polished Magnesium Fluoride	4
	C. Oxygen Annealing of a buried YBCO Ground Plane	7
	D. MCM Fabrication	8
III.	SUMMARY OF PROGRAM ACCOMPLISHMENTS	11
	A. Identification of a Low Epsilon Substrate	11
	B. Optimization of YBCO Film Quality on the Substrate	11
	C. Identification of Microwave and MCM Applications	12
	D. Development of an MCM Structure	12
IV.	LIST OF PUBLICATIONS	13

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SUMMARY

The major objectives of this four year program have been accomplished. A suitable low loss, low dielectric constant substrate for HTS circuitry has been identified and shown to permit the deposition of high quality YBCO films that are comparable to that achieved with lanthanum aluminate substrates. The substrate is magnesium fluoride which has a dielectric constant of 5.3 and a loss tangent of 0.0001 at 77K. The benefits of this technology are higher speed interconnects for Multi-Chip Module (MCM) assemblies applied to digital processing, higher power handling at microwave frequencies applied to multiplexers and other passive components, and lower frequency dispersion and lower loss at millimeter wave frequencies applied to antenna feed networks, T/R modules, and delay lines. We have developed a novel fabrication technique for MCM structures that features an ultra-thin YBCO-covered magnesium fluoride substrate glass-bonded to a metal handle, which provides excellent mechanical support and good heat sinking characteristics. For a sample demonstration of this technology, an MCM structure with a YBCO signal plane that is suitable for microwave/millimeter wave circuitry was fabricated and tested to have excellent electrical characteristics with a YBCO film surface resistance of 1 mohm.

I. INTRODUCTION

The major objectives of this program were: (1) to identify suitable low loss, low dielectric constant substrates and optimize the YBCO deposition process for high quality YBCO films including necessary buffer layers; (2) establish the suitability of these high quality YBCO films on a low epsilon substrate to applications in millimeter wave components and the interconnect technology for Multi-Chip Module (MCM) assemblies; and (3) to develop a technique for processing an HTS MCM structure that can be used for the above applications. This report will first cover the MCM development work accomplished over the last three months of this program and then summarize the significant technical results of the entire four year program.

II. PROCESSING DEVELOPMENT OF THE MCM STRUCTURE

During Phases II and III of this contract, Sarnoff pursued an alternate approach to the MCM interconnect problem using YBCO/bulk magnesium fluoride that is based on glass bonding to a metal substrate. Compared with other ARPA-funded MCM program where multiple epitaxial layers of dielectrics and YBCO films are grown on a base single crystal substrate such as YSZ, our alternate approach has the following benefits:

- It gives superior heatsinking through a metal base.
- Allows the use of a high quality single crystal dielectric for the YBCO film deposition.
- Provides an optional choice for the power plane of the MCM structure to be a thick normal metal instead of YBCO.

Phase II work demonstrated a structurally compatible material system for bonding a YBCO/ substrate sample to a glass/metal handle and also demonstrated thinning and polishing of magnesium fluoride to 10 microns. However, the use of capping layers consisting of yttrium oxide/Ti/Pt/Cu used to shield the glass from the YBCO was not fully successful since these cap layers chemically react with the YBCO when heated to temperatures required for glass bonding to the metal handle. We believe that the Ti and copper interact with YBCO and cause changes in the YBCO stoichiometry. In Phase III, Sarnoff pursued a new approach that can result in the high quality structure shown in Figure 1 that provides low circuit loss at high frequencies for microwave/millimeter wave applications. This structure also provides heatsinking and a low dielectric constant substrate for MCM applications.

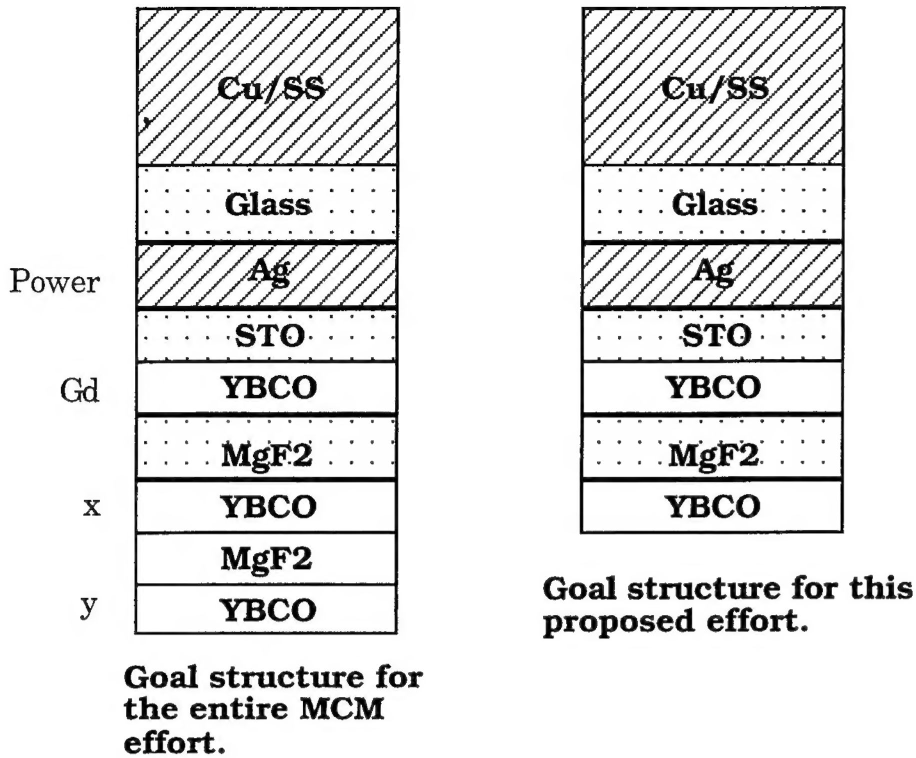

Figure 1. MCM/YBCO Structure Using Ag Cap Layer.

To solve the YBCO cap layer interaction problem, we demonstrated Ag to be an effective cap layer material between the glass/metal handle and the YBCO. The use of Ag could provide, for instance, the power plane for the four layer MCM module, as shown in Fig. 1. Also, Ag on YBCO does not degrade YBCO performance as proven from previous experience at Neocera and it does not require a sticking layer such as Ti or Cr which is reactive with YBCO. The following section discusses our most recent results with the new MCM structure, which includes the demonstration of high quality YBCO films polished MgF_2 substrates, oxygen annealing of YBCO films buried by a thick Ag cap layer, and fabrication of a thin MgF_2 MCM structure suitable for forming microstrip-type transmission structures that are useable for microwave/millimeter wave and MCM interconnect applications.

A. Summary of Development Plan

We divided the fabrication and testing of the MCM/YBCO structure shown in Fig. 1 into 4 major areas of effort. The diagram showing the breakdown of the tasks is given in Fig. 2 with Tasks I and II running in parallel. Detailed descriptions of the tasks are given in the Program Plan for Phase III dated November 30, 1993, that was submitted to ARPA.

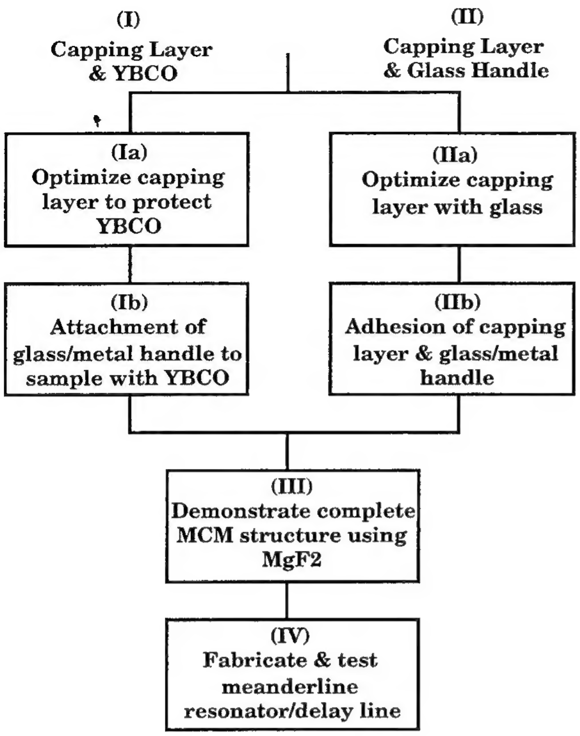

Figure 2. Breakdown of Program Tasks.

B. Optimization of YBCO on Vendor-Polished Magnesium Fluoride

YBCO films were deposited on $LaAlO_3$ wafers to establish a baseline for the film quality. Table 1 summarizes these results. As we can see from the data obtained with the dielectric resonator (DR) test system, the minimum measured Q_o at 24 GHz and 77K is 29,000. From the computed curve shown in Figure 3 of surface resistance at 10 GHz versus the measured Q_0 with the DR test system at 24 GHz, this Q_0 number corresponds to a computed maximum R_S of 0.5 mohms at 10 GHz. These YBCO films are not only of superior quality but also extremely reproducible.

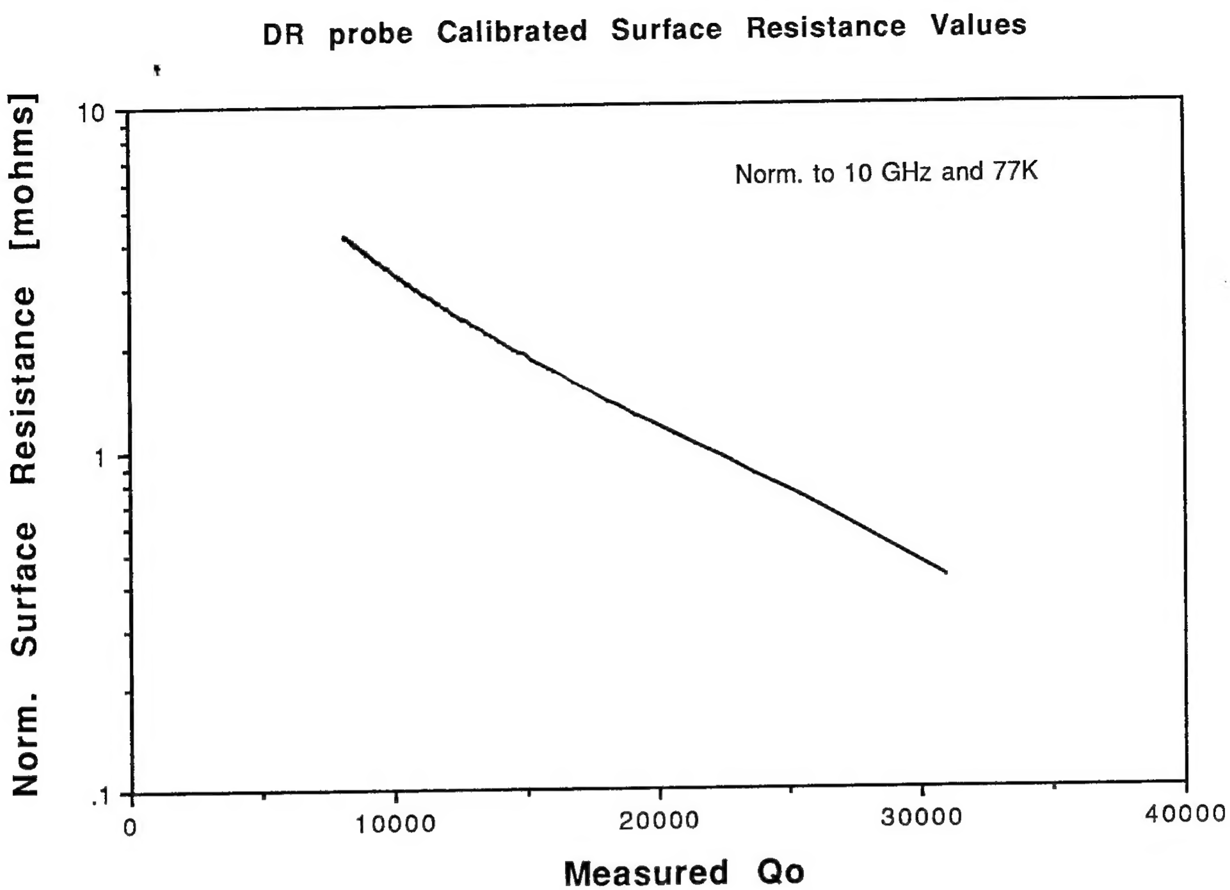

Figure 3. YBCO Surface Resistance at 10 GHz vs the measured Q_0 with the DR Test System.

Table 1.

$YBCO/LaAlO_3$ Samples at 77K

Sample	Q_0 at 24 GHz	R_S (mohms) at 10 GHz
NGL29	29,444	0.50
NGL30	30,424	0.42
NGL32	30,022	0.45
NGL34B	29,605	0.50
NGL35	31,043	0.40

The YBCO film deposition on vendor-supplied MgF_2 substrates were carried out to evaluate the substrate quality as well as the deposition parameters. The substrates supplied to us in the recent past by this vendor (Commercial Crystal Laboratories) have been found to have poor surface quality. This is related to a modified surface processing procedure adopted by the vendor. With constant feedback from Neocera, the vendor has now been able to supply MgF_2 substrates with a high surface quality suitable for growing single crystalline YBCO with superior microwave properties. Figure 4 shows AC susceptibility data obtained on one of these YBCO-covered substrates with MgO and $SrTiO_3$ buffer layers. The films routinely exhibit Tc's of 90K and with transition widths of less than 0.5K. Table 2 summarizes the dielectric resonator Q_0 results for two of these samples. As with the YBCO/$LaAlO_3$ samples, these films are not only of superior quality but also reproducible.

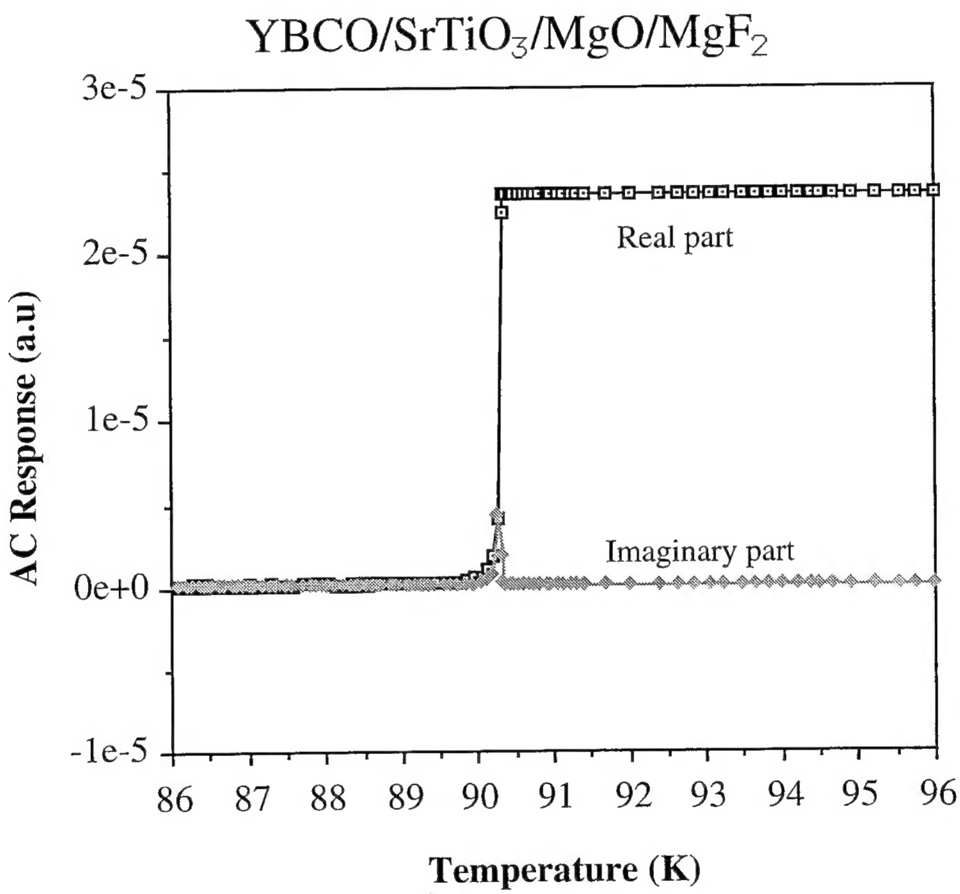

Figure 4. AC Susceptibility Data of YBCO on a Vendor-Polished MgF_2 Substrate

Table 2.

$YBCO/MgF_2$ Samples at 77K

Sample	Q_0 at 24 GHz	R_s (mohms) at 10 GHz
NCF178	26,921	0.62
NCF180	27,900	0.55

C. Investigation of Silver as a Capping Layer

Our investigation of post annealing of Ag-coated YBCO films was conducted with the use of $LaAlO_3$ substrates since the Ag/YBCO interface was being studied and the $LaAlO_3$ substrates are larger, cheaper, and require no buffer layers for the YBCO. The details of this procedure are as follows:

1. Deposit YBCO film on $LaAlO_3$.
2. Measure Q_0 of YBCO directly at 77K and 24 GHz to establish a baseline.
3. Measure Q_0 of YBCO indirectly by measuring through the $LaAlO_3$ substrate.
4. Deposit 5 µm Ag on YBCO. Refer to Figure 5.
5. Measure Q_0 of YBCO indirectly by measuring through the $LaAlO_3$ substrate.

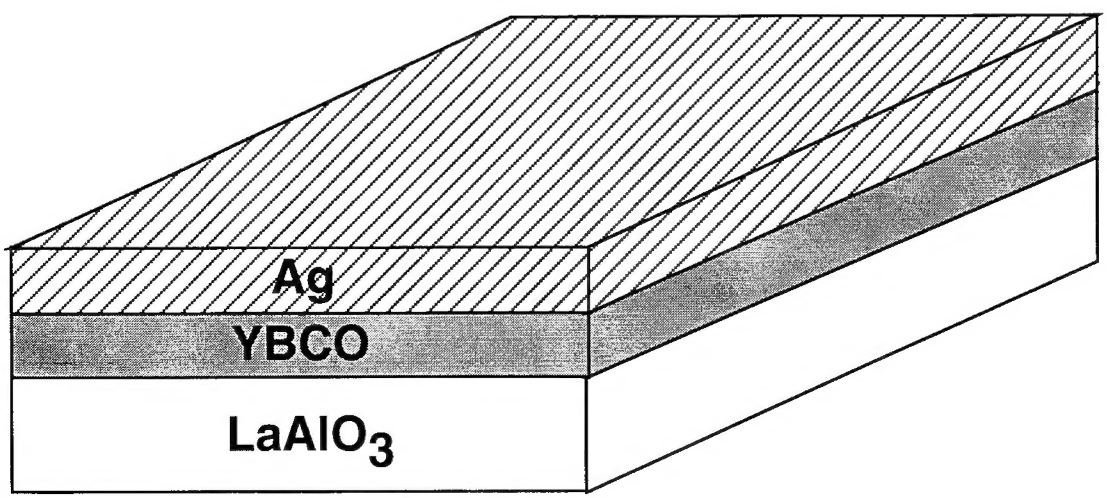

Figure 5. $Ag/YBCO/LaAlO_3$ Sample

Our previous experience indicated that the deposition of Ag onto YBCO films resulted in a drop in Q_0. Two of the YBCO/$LaAlO_3$ samples mentioned above, NGL29 and NGL30, were used for the most recent tests. At 77K and 24 GHz, Q_0 for sample NGL29 as measured through the $LaAlO_3$ substrate is 32,000. After the Ag deposition, Q_0 dropped to 21,000. The sample was then fired in flowing O_2 using the glass firing profile, which reaches a maximum temperature of 625°C. As the sample cooled, the temperature was held at 550°C, a standard YBCO annealing temperature, for 2 hours and then slowly cooled to room temperature. This was to simulate a glass firing cycle. Q_0 did not change significantly. In an effort to increase Q_0, the sample was annealed at 550°C for 5 hours. Q_0 dropped from 21,656 to 20,000. We feel that the elevated firing temperatures for the glass profile may have contributed to the inability to completely recover the sample. However, Q's of 20,000 and Rs values of about 1 mohm should be sufficient as a ground plane for most applications. The results are summarized below in Table 3.

Table 3.

Q_0 for Ag/YBCO/$LaAlO_3$ Samples at 77K and 24 GHz

Sample	Ag (μm)	Q_0 (front)	Q_0 (back)	Comments
NGL29	-	29,444	32,000	As received
	5		21,000	after Ag deposition
	5		21,656	glass profile
	5		20,000	5 hr anneal, 525°C
NGL30	-	30,424	33,241	As received
	5		22,849	after Ag deposition

D. MCM Fabrication

Fabrication of an MCM structure suitable for microwave/millimeter wave applications was investigated. The resulting novel structure consists of a magnesium fluoride substrate thinned to 125 microns and having a YBCO signal layer, a normal silver ground plane, and a glass/metal handle support. The structure is shown in Figure 6. The objective was to demonstrate the ability to deposit a high quality YBCO signal layer on the glass/metal handle supported structure resulting in a assembly that is useful for many microwave/mm-wave applications.

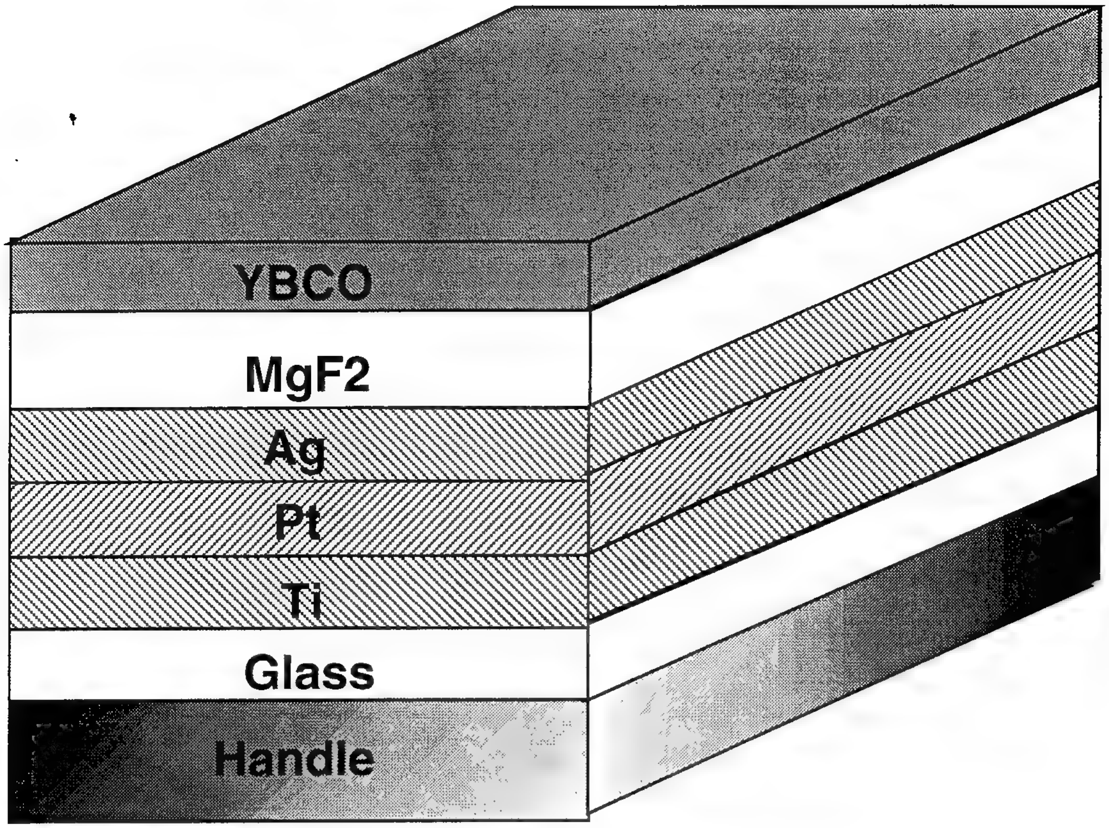

Figure 6. Complete YBCO MCM Structure

Below is a brief outline of the steps that were used to fabricate the MCM sample:

1. Obtain MgF_2 samples, 1 cm x 1 cm x 0.0508 cm, one side polished. Verify that the polish is of superior quality for the deposition of YBCO films.
2. Thin sample to 125 microns thick by lapping and polishing unpolished side of sample. Mark this side with an 'X'.
3. Deposit Ti-Pt-Ag on side with' 'X'. Thickness of Ag is 5 μm
4. Screen Bi_2O_3 glass in powder form onto metal handle.
5. Attach handle to MgF_2 wafer on Ag side.
6. Fire structure to allow glass to flow and bond with Ag and the handle.
7. Deposit YBCO on exposed side of MgF_2.

The YBCO films had to be deposited on a Sarnoff-polished MgF_2 surface, because at that time the vendor's polish did not have sufficient quality for YBCO growth. As was discussed previously, it was only recently that the vendor delivered high surface quality substrates.

Completed YBCO-covered MCM samples with the glass/metal handle gave AC susceptibility data shown in Figure 7. A Tc of 90K and a transition width of about 1K was obtained, but the susceptibility curves are clearly inferior to that shown in Figure 4 for YBCO on single-sided bulk magnesium fluoride with the recent high quality vendor polish. The microwave dielectric resonator tests at 25 GHz and 77K for two samples are shown in Table 4. These results are typical (at the time of this MCM fabrication work) for YBCO films on 10 mil thick MgF_2 substrates without any processing.

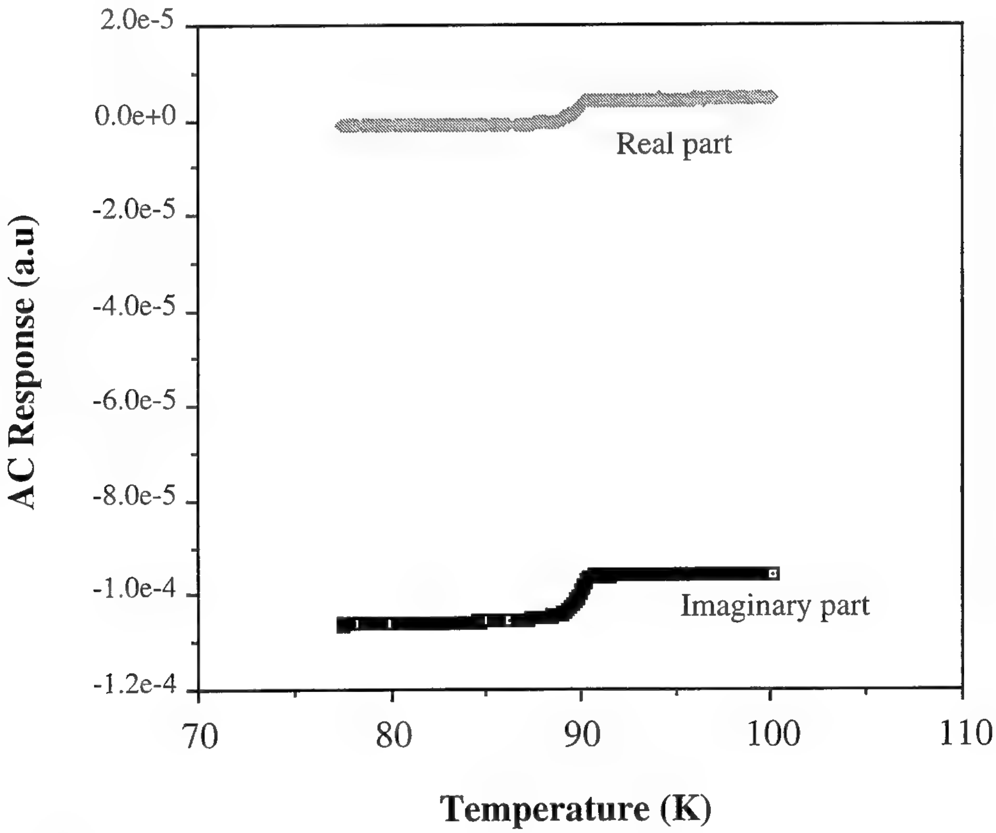

Figure 7. AC Susceptibility Data of YBCO Films on MgF_2/Glass-metal Handle substrates with a Sarnoff-Polished Surface.

Table 4.

Q_0 for YBCO MCM Structures at 77K and 24 GHz

Sample	MgF_2 Polish	Qo	Rs (mohms) at 10 GHz
NCF182	Sarnoff	14,564	2
NCF183	Sarnoff	20,165	1

Due to the depletion of funds and time for this program, we were not able to repeat this MCM fabrication process with the recently obtained high surface quality substrates. However, these MCM results are very significant in showing that the glass-metal handle structure bonded to mechanically thinned magnesium fluoride substrates is compatible with the deposition of YBCO films. The highest measured Qo of greater than 20,000 and an Rs of 1 mohm for the MCM structure YBCO film is a reasonable value for many applications in the microwave band and for low frequency interconnects.

III. SUMMARY OF PROGRAM ACCOMPLISHMENTS

The following is a summary of the achievements that were made during this superconductivity program.

A. Identification of a Low Epsilon Substrate

We successfully achieved and reproduced the deposition of a high quality HTS films on low dielectric constant substrates. The substrate material is magnesium fluoride, which was evaluated with a dielectrometer to have a dielectric constant of 5.32 and a loss tangent of 0.0001 at 77K and measured at about 10 GHz (see R&D Quarterly Status Report for period 8/1/92 to 10/31/92). It has a tetragonal structure, a good hardness of 575 Knoop, and a linear thermal expansion coefficient that closely matches YBCO.

B. Optimization of YBCO Film Quality on the MgF_2 Substrate

YBCO film quality that closely matches that achieved with YBCO on lanthanum aluminate was achieved by using two buffer layers, the first one being MgO and the second being strontium titanate. A dielectric resonator test system was developed under this program to nondestructively probe a YBCO-covered unpatterned substrate up to 5 cm in diameter. Q's of 29,000 and corresponding surface resistance values of about 0.5 mohms were measured with this technique.

The YBCO films on MgF_2 had a transition temperature of 89K and a transition width of 0.5K. Critical current densities of $4x10^6$ A/cm^2 at 77K in zero field were among the highest reported for YBCO films. Patterned meander line resonators using YBCO films on MgF_2 yielded unloaded Q values that were 10X better than copper at 10 GHz.

C. Identification of Microwave and MCM Applications

The low epsilon substrate for YBCO films gives the following advantages for microwave/millimeter wave circuitry and lower frequency MCM interconnects:

1). This technology enables the use of wide lines and thick substrates for greater power handling and lower loss performance. The lower epsilon avoids moding problems and has less dispersion than with higher epsilon substrates such as lanthanum aluminate. Applications include multiplexers and switched filter banks for satellite applications, microwave/millimeter wave antenna beamforming networks, switched time delay for broadband phased array antennas, and up/down converters for satellite communications subsystems.

2). For microwave MCM applications, the low epsilon allows wider lines for thin multi-layer structures which translates to lower loss and low dispersion. Applications include digital beam forming receive modules for multi-beam communications and radar antennas, miniature delay lines for EW systems, and millimeter wave T/R modules.

3). For low frequency MCM modules, the interconnects on the low epsilon substrate gives lower loss and less time delay between IC chips. Applications include digital signal processors for heavy traffic multi-channel communications systems and a high speed switch matrix for data communications.

D. Development of an MCM Structure

We have successfully demonstrated an MCM structure with a high quality YBCO signal plane that is suitable for microwave/millimeter wave circuitry. It has a 125 micron (5 mil) thick low epsilon substrate that is supported by a thick (750 microns) metal handle, which provides good heat sinking as well as mechanical support. The silver ground plane in the demonstration MCM structure could now be replaced by a YBCO/silver combination to form a double-sided HTS structure for all-HTS microstrip circuitry. This processing step was demonstrated by the successful oxygen annealing of a buried YBCO layer through 5 microns of silver on lanthanum aluminate substrates (see Section II.C of this report). The following steps have been accomplished in realizing MCM structures with thinner substrates (down to <10 microns) and with an additional power plane that is shown in Figure 1:

1). We have successfully thinned magnesium fluoride supported by the glass/metal handle to thicknesses <10 microns using a mechanical lapping/chemical polishing technique.

2). STO capacitor dielectric films (2000 angstroms) deposited on YBCO-covered substrates survived the glass deposition and firing environment and then allowed revival of the underlying YBCO film by oxygen annealing.

3). A silver power plane thickness of 5 microns was found sufficient for preventing reduction in the power plane conductivity due to interaction with glass while firing. As mentioned above, oxygen annealing an underlying YBCO film through this thick silver film after submission to glass firing temperatures was also accomplished.

4). A bismuth-based bonding glass was found to have minimal reaction with the silver layer and was able to withstand the 750 degree temperatures during YBCO deposition of the signal layer. Furthermore, the glass bond between the substrate and the support metal handle holds well at 77K and during the lapping/polishing process for thinning the MgF_2 substrate.

5). The coefficient of thermal expansion for the glass/Cu-SS-Cu metal handle matched well to the YBCO-covered magnesium fluoride substrate. The structure holds up well to the thermal cycling required for cryogenic operation.

6). The glass bonding layer was patterned in order to allow oxygen transfer through the silver and capacitor dielectric layers for oxygen annealing the underlying YBCO ground plane.

7). We have successfully demonstrated the deposition of a high quality YBCO signal layer on a Sarnoff thinned and polished MgF_2 substrate with an attached glass/metal handle. Even better quality films can now be obtained using the Commercial Crystal polishing technique as demonstrated with single-sided YBCO-covered MgF_2 substrates (see Section II.B of this report).

IV. LIST OF PUBLICATIONS/REPORTS/PRESENTATIONS

1. Papers Published in Refereed Journals

K. S. Harshavardhan, S. M. Green, A. Pique, K. Patel, R. Edwards, T. Venkatesan, E. Denlinger, V. Pendrick, D. Kalokitis, A. Fathy, X. Wu, M. Rajeswari, and A. Smith, "Microwave Compatible YBCO Films on (001) Magnesium Fluoride Substrates", Applied Physics Letters, Vol. 64, No. 12, pp. 1570-1572, Mar. 21, 1994.

2. Non-Refereed Publications and Published Technical Reports

E. Belohoubek, A. Pique, E. Denlinger, "Superconducting Switchable Circulator", Final Report to NASA-JPL, Neocera Contract No. NAS7-1292, July 25, 1994.

3. Presentations

1. K. S. Harshavardhan, S. M. Green, A. Pique, K. Patel, R. Edwards, T. Venkatesan, E. Denlinger, V. Pendrick, D. Kalokitis, A. Fathy, X. Wu, M. Rajeswari, and A. Smith, "YBCO

Films on Low Dielectric Constant MgF_2 Substrates", Materials Research Society Meeting, October, 1993, Boston, MA.

2. D. Kalokitis, "Intermodulation Distortion in YBCO Narrow Band Filters", High Power Superconducting Microwave Technology Work Shop, 1994 IEEE G-MTT Symposium, May 23, 1994.

3. E. Denlinger, "High Performance YBCO Films on Low Dielectric Constant Substrates", High Temperature Superconductor Materials Meeting, Arlington, VA, August 31, 1994.

4. A. Fathy, D. Kalokitis, V. Pendrick, E. Denlinger, H. Johnson, A. Pique, K. Harshavardhan, E. Belohoubek, "Miniature Circulators for Microwave Superconducting Systems", 1995 IEEE Microwave Symposium, May, 1995, Orlando, FL.